LCA Case Studies

An Environmental Evaluation of Mechanical Systems Using Environmentally Acceptable Refrigerants

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DOI: http://dx.doi.org/10.1065/lca2000.04.024

Abstract. New hydrofluorocarbon refrigerant gases in domestic refrigerators require the use of the newly developed synthetic lubricants. Research carried out so far indicates that the hermetic compressor used in these refrigerating systems is one component that is likely to be directly influenced by this change in working fluid. This may affect system performance as well as system durability such that a potential environmental improvement may result in a shift in environmental pollution. An environmental evaluation, using a life cycle assessment (LCA) computational tool, is carried out to study the influence of the individual components on the overall product environmental contribution. The manufacture and the recovery of the refrigerants addressed in this study were also included in this evaluation. In this LCA study, the hermetic compressor was found to contribute significantly to a number of impact categories as compared to other product components of concern. This becomes of primal environmental significance in view of the possibility that tribological characteristics, due to the presence of the new refrigerant/lubricant combinations, may influence its performance.

Keywords: Acidification; CFC-12; domestic refrigerator; use phase; global warming potential; HFC-134a; human toxicity; LCA; Life Cycle Assessment; lubricants; refrigerant; refrigerants; refrigerator; components; summer smog; sustainable development; viscosity

Introduction

Due to international legislation, new hydrofluorocarbon (HFC) refrigerants have been developed and are currently used as a transitional, environmentally friendly alternative to chlorofluorocarbon (CFC) refrigerants in many domestic refrigerators. Compared to CFCs, HFCs have removed the ozone depletion potential (ODP) and lowered the global warming potential (GWP) (PAPASAVVA et al., 1998). Although it is argued that better alternatives, such as hydrocarbon (HC) refrigerants already exist (PAPASAVVA et al., 1997), an assurance on the availability of HFCs is required if the CFC phase out is to be completed successfully (DOE, 1996). The high initial investment in developing this transitional refrigerant (PAPASAVVA et al., 1997) and until safety considerations are addressed more rigorously, HFC production for the domestic refrigeration industry is at present on the increase (DOE, 1996).

The rate of production of domestic refrigerators has and will continue to increase phenomenally worldwide (KUSIK et al., 1991). The environmental concerns that lie here are great despite the minimum amount of refrigerant each unit holds. Designing a product for the environment involves the consideration of the energy efficiency in the product use phase as well as the extension of the useful life of the product or its components (JENSEN et al., 1997). A change of refrigerant affects the compressor capacity (GULDBRANDSEN et al., 1986) as well as the tribological characteristics at high pressure surface contacts within the hermetic compressor (CIANTAR et al., 1998; CIANTAR et al., 1999). Both factors influence the system efficiency but the latter may also influence product durability due to the increased frictional energy. New lubricants are developed to improve lubricity as well as miscibility with the new refrigerants but these too may affect system efficiency due to increased work by the compressor and reduced thermal conductivity at the heat exchangers (KUSIK et al., 1991). It is still debatable whether refrigerator lifetime should be increased or reduced but any ensuing problems, as a result of the new lubricant/refrigerant combinations, may not necessarily mean complete product failure. An implication could be that during the first few years of operation system performance might deteriorate due to issues of friction and wear. The arising conflicts and tradeoffs required to address the above ensuing constraints are likely to have been overlooked when seeking a CFC-substitute but need to be addressed to ensure the development of a sustainable product.

Considering this emerging research problem, these indirect design consequences (CIANTAR et al., 1999) have environmental effects which a life cycle assessment (LCA) may identify within the product system life cycle. As argued by Wenzel et al (WENZEL et al., 1997), LCA must look at the overall service provided by the product to the user. Hence, a change in refrigerant needs to be looked at from the overall service provided by the product. It would be a misunderstanding to look at the environmental impacts of the refrigerant itself if, for example, the energy consumption in the refrigerator's use stage is altered by the new working fluid. Alternatively, it would be misleading to look at the energy consumption in the product use phase if this new change will alter the compressor's life span. In short, it is important to prevent a poten-

tial environmental improvement from becoming a shift in environmental pollution.

The aim of this study was to carry out an LCA study on the identical components within a CFC-compliant and an HFC-compliant refrigerator (CIANTAR et al., 1999) in an attempt to identify how the mechanical system compares with the rest of the components within this product system. This is essential since this research work focuses on the hermetic compressor to ameliorate system performance. The outcome of this study together with experimental work, currently being undertaken to assess and compare the technical life and energy consumption of hermetic compressors working in CFC-12 and HFC-134a environments, will reveal the implications of this change in refrigerant from an environmental viewpoint. Dissimilar items, like the refrigerant, also need to be assessed to identify the environmental implications of this change in working fluid. The impact categories focused upon for the product components were global warming, acidification, human toxicity, nutrification and summer smog and extended from the production of materials, component manufacture, transport, assembly, use and disposal. Refrigerant production and disposal was also taken into consideration to study implications on global warming and acidification. Lubricant production and disposal was ignored throughout this study due to a lack of information available on the public domain, however, its possible significance on the outcome of the results needs to be addressed more fully.

1 The System and System Boundaries

It is beyond the scope of this study to emulate formal LCA procedures (BS 1997; BS 1998; BS 1999). In this report it was considered more appropriate to emphasise the assumptions necessary to complete this study rather than documenting the methodology. For a domestic refrigerator this has been exhaustively documented elsewhere (WENZEL et al., 1997) and illustrates that the environmental implications are unquestionable. The use of a commercial computational tool, PEMS™ (PIRA, 1998), to carry out this study may be seen as addressing available standards but this was not of primal concern. Although LCA studies generally try and quantify the impacts, this study is more concerned with undergoing a qualitatively (WEIDEMA, 1994) study in an attempt to acquire comparative information about the individual components making up the system. The assumptions made influence all the product components and therefore such comparisons were feasible. The importance of such qualitative information will help establish implications that may result from a reduced product life span due to reduced system performance resulting from a change in lubricants. Accelerated compressor functional tests will help identify differences between the alternative lubricant solutions, operating under various scenarios, allowing the most environmentally attractive solution to be considered. Once the potential impacts of the individual components are known, the effect of change brought about by the different lubricants and operating scenarios can be estimated quickly using a process termed as Δ (delta)-modelling (WENZEL et al., 1997). Knowledge acquisition, on areas that are likely to influence the product use phase, will be acquired through experimentation helping to refine the LCA study further.

This LCA approach will also help carry out a critical assessment between the method and data used in PEMS™ and the data and methods used in other studies. This assessment, although not emphasised in this report and not necessarily implying a fail-safe approach, will shed light upon the credibility of this research work.

1.1 Defining the system

The system under investigation consisted of a fridge-freezer having a total gross volume of 289 litres and a total net volume of 267 litres. This appliance utilises a fractional compressor (GULDBRANDSEN et al., 1986) identical to that being laboratory tested under a variety of refrigerant/lubricant combinations (CIANTAR et al., 1999). On a mid-range thermostat setting and at an ambient temperature of 20°C, the unit can maintain an internal refrigerator temperature of 5°C. Other secondary qualities include self-defrosting, evaporation of the water from defrosting, shelves and boxes as well as a refrigerant charge of 115 grams. A number of assumptions had to be made to make the product manageable and which need to be highlighted to ensure that this study is followed coherently.

Whilst presuming that the refrigerator is CFC-compliant, it was assumed that the refrigerant used is CFC-12 since the domestic appliance was the principal application for this refrigerant (DOE, 1996). Rigid polyurethane (PU) used in refrigerators was blown using CFC-11 but this was not a critical factor to the study since it only drastically influences the ODP as well as the direct GWP. Since these gases have been phased out, our immediate concern is the indirect GWP (henceforth taken to mean the GWP resulting from the burning of fossil fuels) which makes the use of HFC-134a more detrimental since its manufacture is more energy intensive (Papasavva et al., 1998). It should be mentioned, however, that HFC-134a cannot be used as a blowing agent (DOE, 1996) but instead other HFC blends have been developed. In view of the lack of information retrieved on the latter, as well as its energy implications already mentioned, the PU-foam blower was assumed to be HFC-134a.

Presuming that the refrigerator is HFC-compliant, it was assumed that both the refrigerant and the blowing agent are HFC-134a. **Table 1** summarises the differences between the two alternative cases for the refrigerant and blowing agent assumed.

Table 1: The type of refrigerant and blowing agent assumed

	Refrigerant charge	Blowing agent for PU-foam
Case 1	CFC-12	HFC-134a
Case 2	HFC-134a	HFC-134a

Another assumption was due to a difference between the molecular weights of the CFC-12 and the HFC-134a compounds (PAPASAVVA et al., 1998). Mechanical systems work-

ing in a CFC environment may require a different refrigerant charge than those working in an HFC environment for the same cooling capacity. The influence of this is presently being experimentally investigated and in this study it was assumed that the masses of the compounds are equal for the two product types. Due to the energy of production implications previously mentioned, if more HFC refrigerant is required to attain the same cooling capacity attained with CFCs, then this is likely to increase the environmental impact.

During refrigerant charging and foam blowing, as well as during the product lifetime, no leakages were assumed to occur. This is undoubtedly unrealistic but any leakages for the CFC and HFC compounds are likely to be relatively equal given the number of products being produced and utilised worldwide. Furthermore, prior to complete product disposal all refrigerant and blowing agent in either of the two instances were assumed to be fully reclaimed. The reason for this being that HFC-134a contributes less to the GWP only if both gases (HFC-134a and CFC-12) are released directly into the environment. These assumptions ensure that the GWP due to the direct effect of the CFC refrigerant will not overcast our principal aim of this study, that is, the indirect GWP since the direct effect will be approximately 87% higher for CFCs (PAPASAVVA et al., 1998). To accommodate this assumption, the energy required for the recovery of the refrigerant and the foam blower was included in this study utilising the inventory data as given in Section 2.2.

The refrigerators were assumed to be completely landfilled at the end of their *first* lifetime. In this study, this was assumed to be approximately 13 years although in the UK it was found to be less (OECD, 1982). No materials were assumed to be recovered prior to their disposal. This fact is unrealistic but in the UK, for example, recovering and recycling of plastics from white goods, although carried out, is not seen as cost effective (DTI, 1999). Also, as argued in (WENZEL et al., 1997), at the end of their useful life refrigerators may become a source of secondary materials but they are unlikely to become a source of primary materials. Polyurethane foams, for example, can only be reused after much processing because they are contaminated with the blowing agent and this too depends on available logistics (DIETRICH et al., 1996; WEIGAND et al., 1999). Environmental problems arising from the landfilling of domestic appliances is the second most problematic in landfill use (JOHANSEN et al., 1997) and as yet emissions to ground and air are unknown (DTI, 1999) and were hence overlooked here. The reasons for assuming complete landfilling were twofold. Firstly, allowing for 100% landfilling, with no shredding or other processing required, resulted in little energy consumption to be accounted for in the disposal stage which would have influenced the contribution to the indirect GWP from product components and the refrigerant. The second reason is due to the fact that there is a tendency that refrigerators are cascaded unto other markets, the second hand market in particular. Although this has environmental benefits it was disregarded for it would be difficult to know what fraction of refrigerators are exported to developing economies where the emissions of CO_2 are not enforced by the Kyoto Protocol (CAMPBELL et al., 1998). This could imply that gases are discharged directly into the atmosphere once the refrigerator is disposed of. Furthermore, the production of electricity may result in more CO_2 emissions implying a higher indirect GWP.

The product under consideration is manufactured and marketed primarily in the UK although some components were known to be purchased from different regions of the world. However, this study was performed relative to the technology used for the generation of electricity for the production of raw materials and the manufacturing processes. Oil, natural gas and coal, average values of which were obtained from the European electricity network (UCPTE) (PIRA, 1998), were individually compared for the manufacture and recovery of the refrigerant compounds. These were found to account for approximately 35%, 35% and 18% respectively of the total fuel consumption for the generation of primary energy in the UK in 1998 (BP, 1999). A UK mixed fuel scenario, consisting of 50.5% coal, 8.3% oil, 13.5% natural gas, 20.1% nuclear, 4% hydro and 3.6% imported from France (PIRA, 1998), was also adopted for the refrigerant compounds and for the manufacture of the fridge freezer components. Obtaining environmental information using different electricity generation technologies for the refrigerant production and recovery should emphasise that the indirect environmental benefits in switching to alternative refrigerants is very much dependant on the manufacturer due to the choice of supplier.

Another assumption resulted from the burdens arising during the manufacture of the materials and the product components. Overheads, process emissions to air and water, material waste, litter, noise, etc. were not analysed in this study. The reason being that whether a CFC refrigerator or an HFC refrigerator is being manufactured relatively equal quantities arise. Their significance increases if the life span of the HFC refrigerator (currently being experimentally investigated) increases or decreases with respect to the refrigerator it is replacing due to the change in refrigerant/lubricant combination. A difficulty arises when it is necessary to filter out personnel activities, like litter, which would occur anyway whether or not a product is being manufactured. This was not investigated throughout this study and the major burden to be considered was to allow for heating (8 kW), ventilation (4 kW) and lighting (2 kW) of the shop floor. The outcome of this assumption, although unlikely to influence the results, is embedded in the findings.

Finally, for either of the CFC and HFC compounds assumed (→ *Table 1*), the transportation during their chemical synthesis was ignored. This is because the transportation is relatively identical in both cases and negligible as compared to the manufacture and disposal phases (PAPASAVVA et al., 1998). With regards to the product system the consumption of energy, particularly for the manufacturing processes and the type and distance covered by the transportation sector, had to be assumed and are given in **Table 2**. The significance of these assumptions was tested, where appropriate, by means of a sensitivity analysis as outlined later on in the study.

Table 2: Bill of materials for the reference product and transportation details, adapted from (Wenzel et al., 1997)

Item	Material[a]	Total weight in grams	Transportation type[b]	Distance covered in km	Manufacturing processes included[c]	Ancillary substances[d,e]	Weight in grams
Cabinet							
Steel cabinet	Steel, plain Epoxy resin	23,478.65 659.5	A B	300 250	Punching, welding, surface treatment, etc.	Water Salt Surfactant Phosphoric acid	26,766.76 30 50 4
Inner box	ABS sheet	4,432.2	A	300			
Compressor box	ABS sheet	559.4	A	300			
PU-foam	Polyurethane	6,242.46	A	150	Foaming	HFC-134a	453.9
Compressor with accessories (subcontract)	Steel Copper Aluminium PVC, brass, rubber	7,289.1 1,366.7 182.2 91.1	A C C C	500 150 150 150			
Pipes for compressor	Copper pipe	13.35	B	150			
Refrigerant	CFC-12 or HFC-134a	115	Assumed identical for both	Assumed identical for both			
Evaporator	Aluminium	1,788.9	A	300			
Condenser	Steel pipe	484.6	B	300			
Pipe for condenser	Copper pipe	26.7	B	150			
Drying filter	Copper Zeolite	37.25 4.14	B	300			
Thermostat	Steel Plastics	56.75 56.75	C B	150 300			
Sensor / thermostat	PVC pipe	33.38	C	150			
Wiring	Copper PVC Steel Brass	243.84 93.79 18.76 18.76	B B B B	150 200 200 150			
Lamp panel	ABS	126.83	A	300	Injection moulding	Water	747.6
Lamp screen	PVC	29.37	B	300	Injection moulding	Water	226.95
Lamp socket	Steel Plastic	18.02 6.01	C C	150 150			
Light bulb	Glass Brass	13.89 3.47	C C	150 150			
Hinge fittings	Stainless steel	173.55	B	300	Punching, etc	Water	106.8
Hinge fitting threaded portion	Steel	272.34	B	300	Punching, etc	Water	3,337.5
Mounting rail	Steel, plain	1,628.7	A	300			
Base plate	Galvanised steel	237.63	A	300			
Door							
Door casing	Steel sheet Epoxy resin	5,673.75 209.6	A B	300 250	Punching, welding, surface treatment	Salt Detergent Phosphoric acid Water	8 16 0.267 10,680
Door lining	ABS sheet	2,403	A	300			
PU-foam	Polyurethane	1,969.125	A	150	Foaming	HFC-134a	287.03
Sealing frame	PVC	440.55	B	250			
Handle	PVC	300	B	300			

Table 2 cont'd: Bill of materials for the reference product and transportation details, adapted from (WENZEL et al., 1997)

Item	Material[a]	Total weight in grams	Transportation type[b]	Distance covered in km	Manufacturing processes included[c]	Ancillary substances[d,e]	Weight in grams
			Accessories				
Thread shelves	Steel Epoxy powder	3,204 106.8	B B	300 250	Cutting, welding, surface treatment	Salt Surfactant Phosphoric acid Water	5 8.5 0.9 8,343.75
Coverplate	PVC	124.7	B	250			
Front rim	PVC	182.9	B	250			
Glass shelf	Glass	0.5	B	200			
Various plastic boxes	PVC	2,213	B	300			
			Packaging				
Packaging	Corrugated cardboard	4,872.75	B	300			
Plastic bag	Polyethylene	140.2	B	250			
Door support	Expanded polystyrene	18.69	C	50			
Base frame	Wood	2,136	B	300			
			Miscellaneous				
Other steel items	Steel	26.7	B	300			
Rubber items	Rubber	20.03	B	100			
Other ABS items	ABS granulate	87.84	A	300	Injection moulding	Water	523.32
Nylon items	Nylon	8.01	B	100	Injection moulding	Water	53.4
Adhesive tape	LDPE, film	18.69	B	100			
Lupolene items	PVC	5.34	B	300	Injection moulding	Water	40.05
Acetal items	PVC	53.4	B	300	Injection moulding	Water	400.5
Other small items	Steel	232.29	A	300			

[a] Material retrieved from available sources may differ from the type used in the product
[b] Transportation details: Type A – truck > 25 tonnes, average road
Type B – truck > 7.5 tonnes, average road
Type C – van < 3.5 tonnes, average road
Note that the transportation burdens were dependent on the useful load on the vehicle
[c] Only manufacturing processes where the use of ancillary substances was necessary are included
[d] Other ancillaries, such as compressed air, electrodes, water for general use, nitrogen for blowing when brazing, etc. were all assumed but not shown here – their influence was not critical to the study
[e] Transportation details for ancillary substances, although considered, are not shown here

1.2 Data acquisition

Due to the commercial sensitivity of the refrigerator data, a synthetic pathway for data acquisition was required to carry out the assessment. The information required for the inventory of the refrigerator items and quantities was obtained using literature provided by the manufacturer. Information on the material content, component weights, manufacturing processes and ancillary substances of the different modules within the product system was obtained from (WENZEL et al., 1997). Details required for the chemical production and recovery of the refrigerants were obtained using the *Life Cycle Warming Impact* (LCWI) adopted from (PAPASAVVA et al., 1998). This LCWI was calculated as a measure of the CO_2 released due to the energy required for raw material extraction and purification and conversion into the two refrigerant compounds as these were found to be the most significant (KUSIK et al., 1991). The value of energy used included both the thermal and the electrical energy used at the chemical plant. Details of the environmental impacts arising due to the processes of the various material production, energy consumption, transportation and other related burdens were retrieved from electronic databases (PIRA, 1998) which were updated regularly. These latter data sources are not directly related to the manufacture of the functional product itself but are interpreted from similar materials, processes and technologies.

Table 3: Values of energy used in the calculation of the impact potentials

Compound	Functional Unit Quantity	Molecular Weight[a]	Number of Moles[a]	Energy for the Production of One Mole[a]	Energy for the Recovery of One Mole[a]	Total Energy of Production	Total Energy of Recovery
	g	g/mole		kWh/mole	kWh/mole	MJ	MJ
CFC-12 Refrigerant	115	121.0	0.95	1.123	0.121	3.84	0.41
HFC-134a Refrigerant	115	101.0	1.14	1.660	0.101	6.81	0.42
Foam Blower	740	101.0	7.33	1.660	0.101	43.8	2.67

[a]Values obtained from (PAPASAVVA and MOOMAW, 1998)

2 Results

2.1 The refrigerant and foam blowing compounds

In this study, focus was applied to the most significant impact potentials, that is, indirect GWP and acidification. These were identified significant by carrying out a valuation procedure similar to the one carried out for the refrigerator components given in **Fig. 3** and **Fig. 4**. For these compounds, however, this assessment was not included in this report for reasons of brevity. Contributions to either of the two due to the manufacture and disposal of the CFC-12 and the HFC-134a compounds under four different fuel scenarios were assessed. **Table 3** gives the values for the total energy, that is, the process energy and the calorific value, for the synthesis and recovery of either of the refrigerant compounds and the foam blower and these were included in the LCA study. The consequent GWP (kg of CO_2 equivalent) and acidification (kg of SO_2 equivalent) characterisation results for the refrigerant LCA model were obtained as shown in **Fig. 1** and **Fig. 2** respectively.

2.2 The refrigerating unit

2.2.1 The impact categories

Although **Fig. 3** shows the impact assessment for the whole of the refrigerator it was difficult to determine which impacts are important to focus on. Uncertainties arising from such a statement were dealt with by using several valuation procedures in an attempt to identify trends. With the computational tool used throughout this study this valuation technique was the most appropriate. Due to reasons of space the outcome of the different valuation techniques adopted, including Problem Oriented (→ *Fig. 4*), Ecoscarcity and Tellus, are not all given in this report. However, as **Fig. 4** depicts, all three confirmed that abiotic depletion, global warming, acidification, human toxicity, nutrification and summer smog were found to be the most significant environmental impact categories.

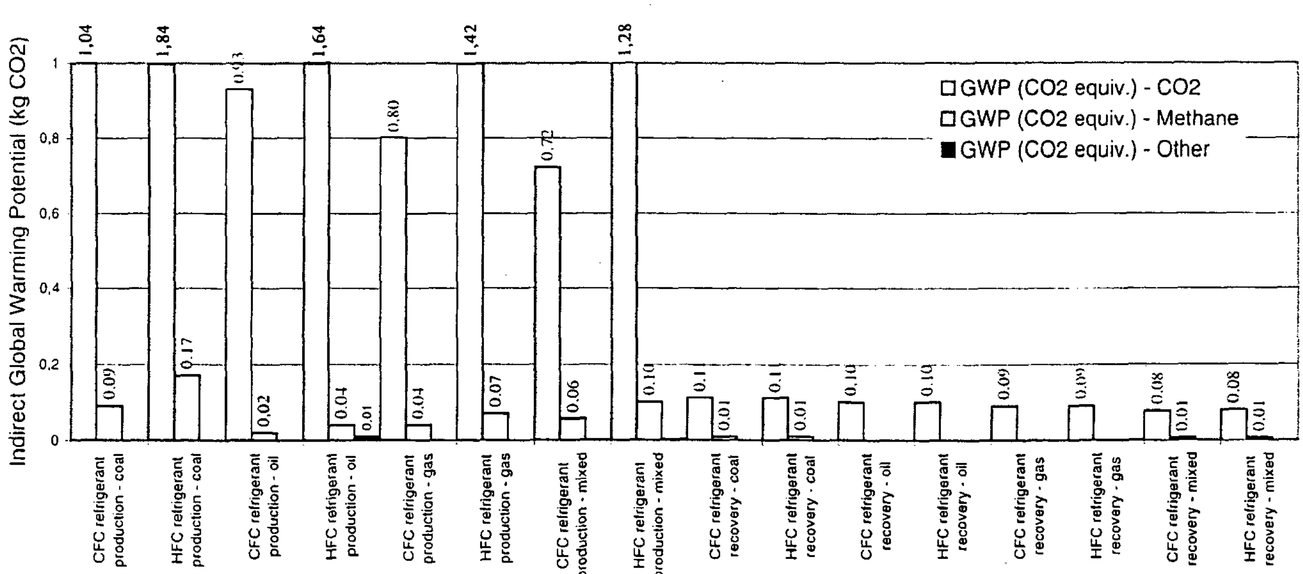

Fig. 1: The indirect contribution to GWP due to the production and recovery of the refrigerant using coal, oil, gas and a mixed fuel scenario as the electricity source

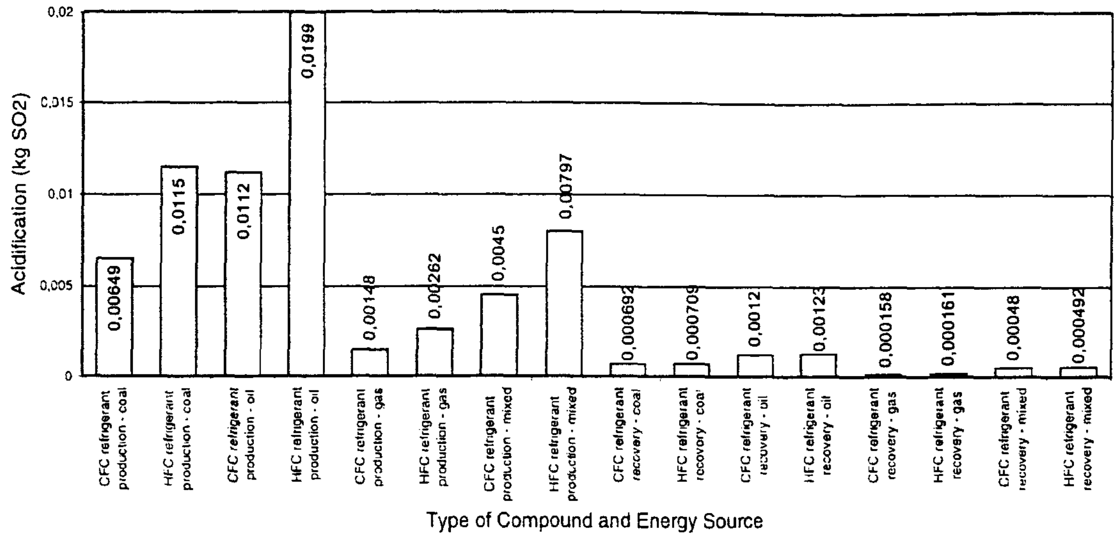

Fig. 2: The contribution to acidification due to the production and recovery of the refrigerant using coal, oil, gas and a mixed fuel scenario as the electricity source

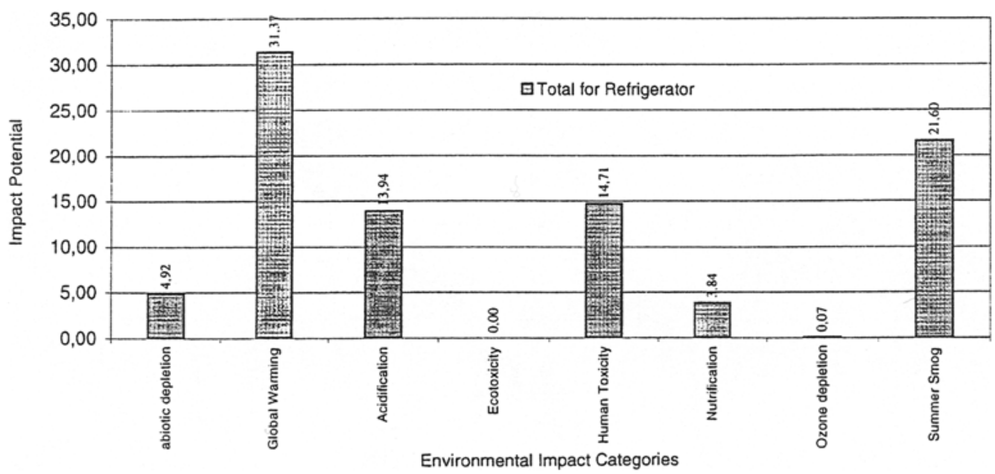

Fig. 3: The environmental exchanges as well as their impact potentials occurring over the product lifetime

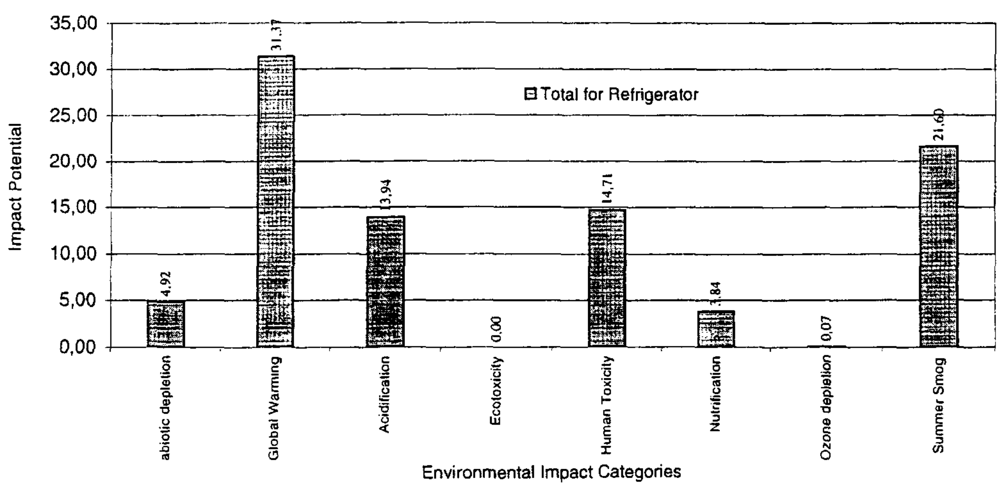

Fig. 4: Problem Oriented valuation

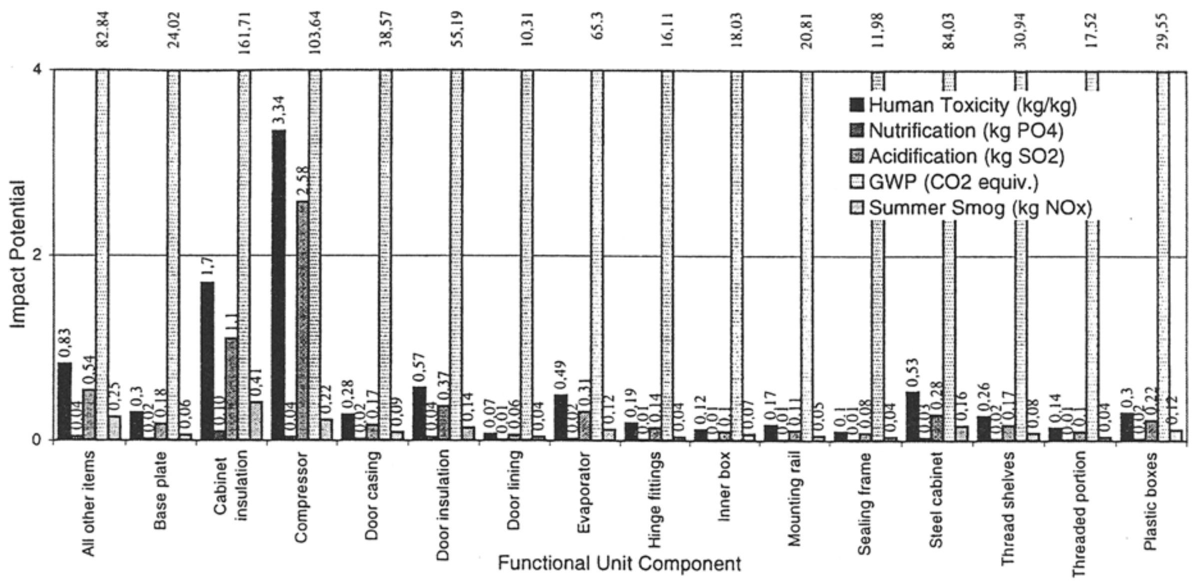

Fig. 5: The most significant functional unit components with the GWP contributions combined for clarity

The energy in the product's use phase, taken to be 40% of the entire lifetime, is included in these characteristics and taken to be as a low voltage of the mixed fuel type. This significantly influences the abiotic depletion (the use of fossil and mineral reserves) as well as global warming as shown (→ *Fig. 3*).

2.2.2 The significant components

It was essential to determine which components making up the functional unit were contributing most to these categories (**Fig. 5**). The energy utilised throughout the lifetime of the product was not included in this analysis. Although of significant importance when laboratory tests address this issue fully, in this study it was ignored due to its significant contribution to all of the mentioned impact categories. In so doing, the reader is assisted in following the analysis more comprehensively by focusing on the contribution of the component materials. To facilitate the analysis, a column showing the contribution of all the other components which make up the functional unit but which they alone do not contribute significantly compared to those components that do, is also included.

It should be noted that the impact potentials identified above assume a type and quantity of energy used for the production of the components. To test the significance of these assumptions on the production of raw materials and the manufacturing process the analysis was repeated and its outcome given in **Fig. 6**. This time only the production of the raw materials, the manufacturing of the components as well as the transportation were assumed whilst the energy content used for the production of the components was ignored. Note

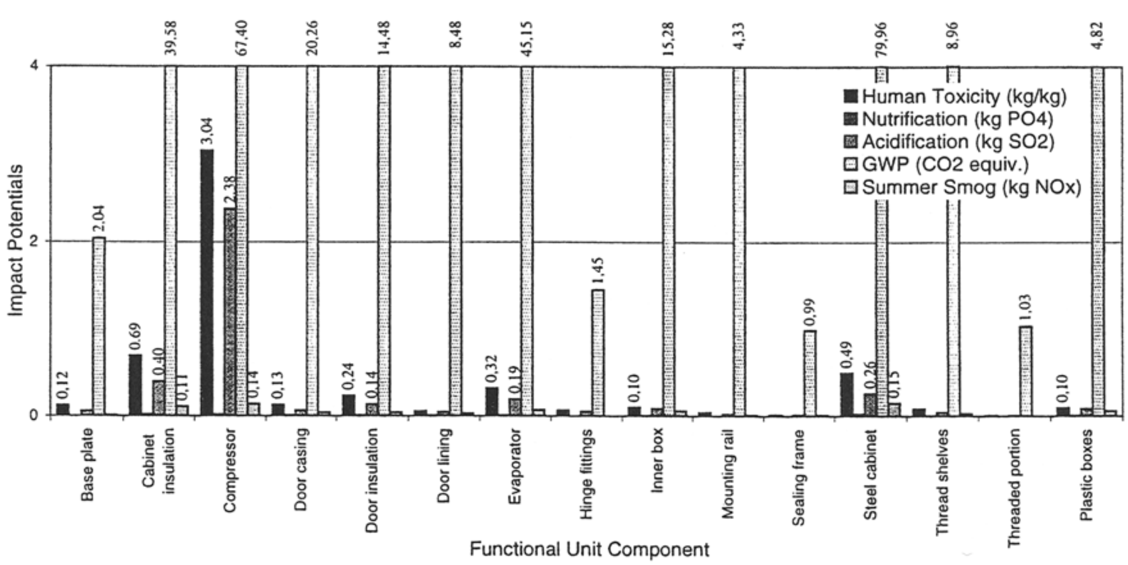

Fig. 6: The most significant functional unit components with the GWP contributions combined for clarity, assuming no energy of production

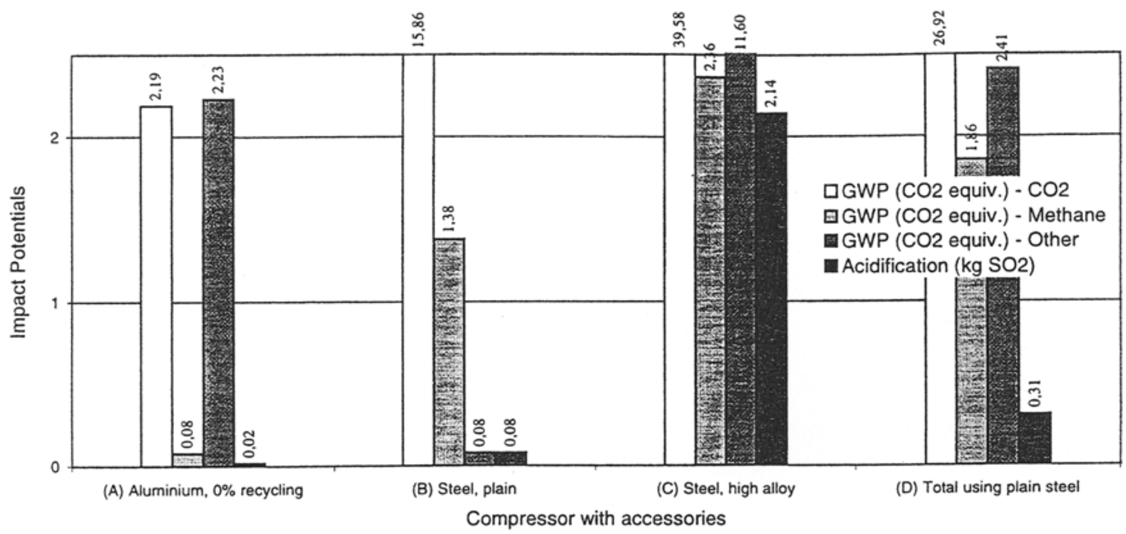

Fig. 7: The effect of steel and aluminium making up the compressor on the GWP

that the items contributing to approximately 100 grams of impact potential were unlabelled for reasons of clarity. The transportation too was investigated further as done for the energy consumption but this was found to have minimal influence over the results. For reasons of brevity this analysis was not included in this report.

Due to the significance of the compressor on the outcome of the result (→ *Fig. 6*) this was investigated further by varying the steel from a high alloy steel to a plain steel. Although this may not be realistic it is only included to help quantify the effect the choice of material has on such a component. The hermetic compressor is of a very robust design and identifying an appropriate material will surely influence the overall environmental consequence as shown (**Fig.** 7). The contribution to the GWP was found to half whilst the influence of acidification was reduced considerably (→ *Fig. 7*, columns (B) and (C) respectively). When obtaining the characteristics shown in Fig. 7, the electricity due to the component manufacture was not taken into consideration. Nonetheless, considering the processes required for the manufacturing of hermetic compressors, such as casting, welding, etc., these would have resulted in a significant contribution to the environmental impacts due to the amount of energy utilised. More insight into the implications of altering materials need to be gathered since this may have product life extension implications too.

Although not shown in Fig. 6 for reasons of clarity, during this study it was evident how much the compressor influenced the GWP from different sources other than CO_2 and methane. Columns (A) and columns (D) in Fig. 7 were included to analyse these findings further. Columns (A) and columns (D) show how high the influence of aluminium is on this form of GWP compared to the total influence of all the other materials. The high alloy steel too accounts for a high contribution although plain steel does not (→ *Fig. 7*, columns (C) and columns (B) respectively). Note that in Fig. 7, only the aluminium and steel making up the com-

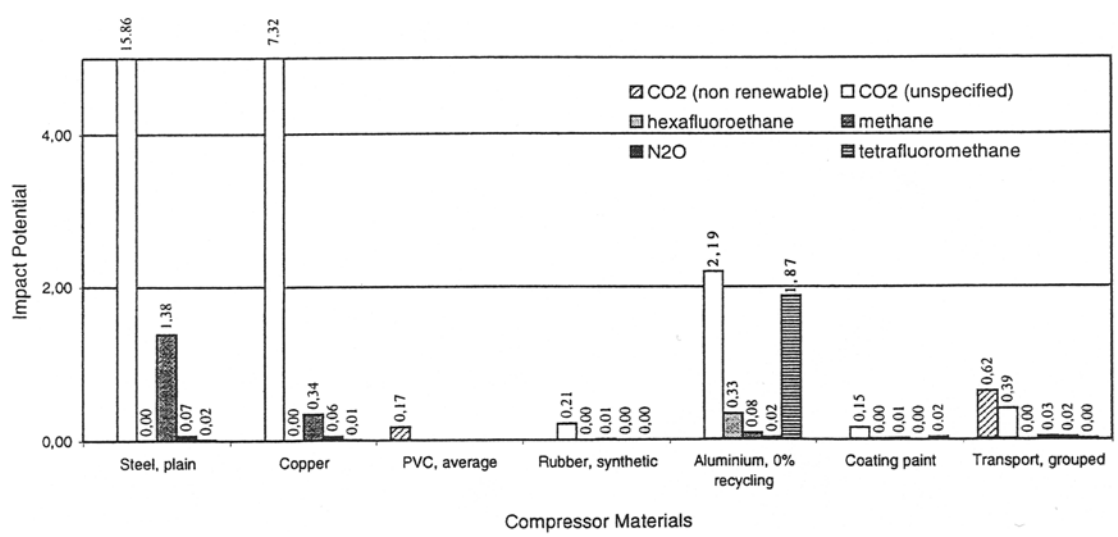

Fig. 8: The contribution of the individual compressor components to the indirect GWP

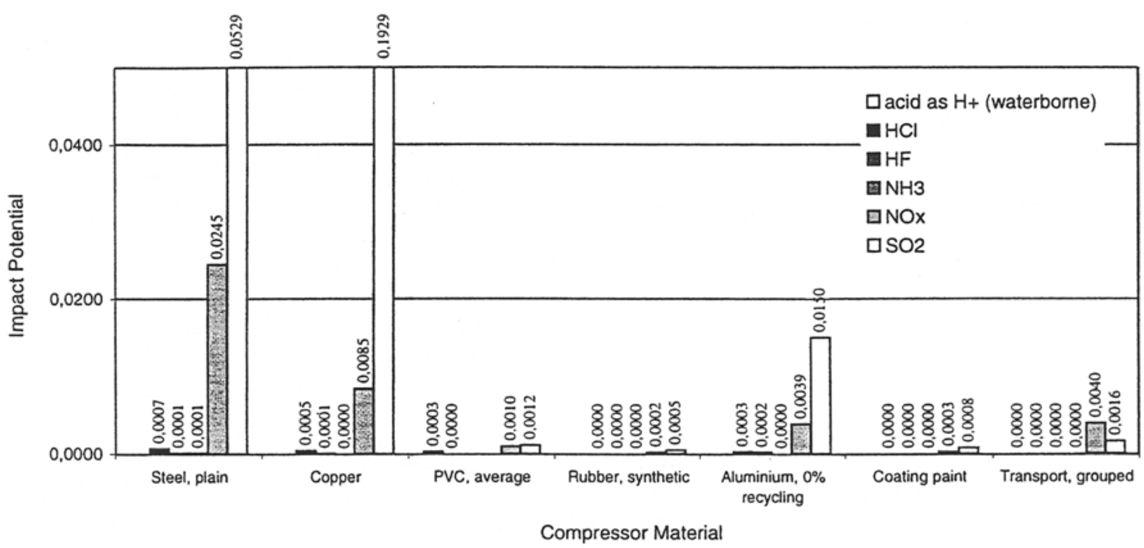

Fig. 9: The contribution of the individual compressor components to acidification

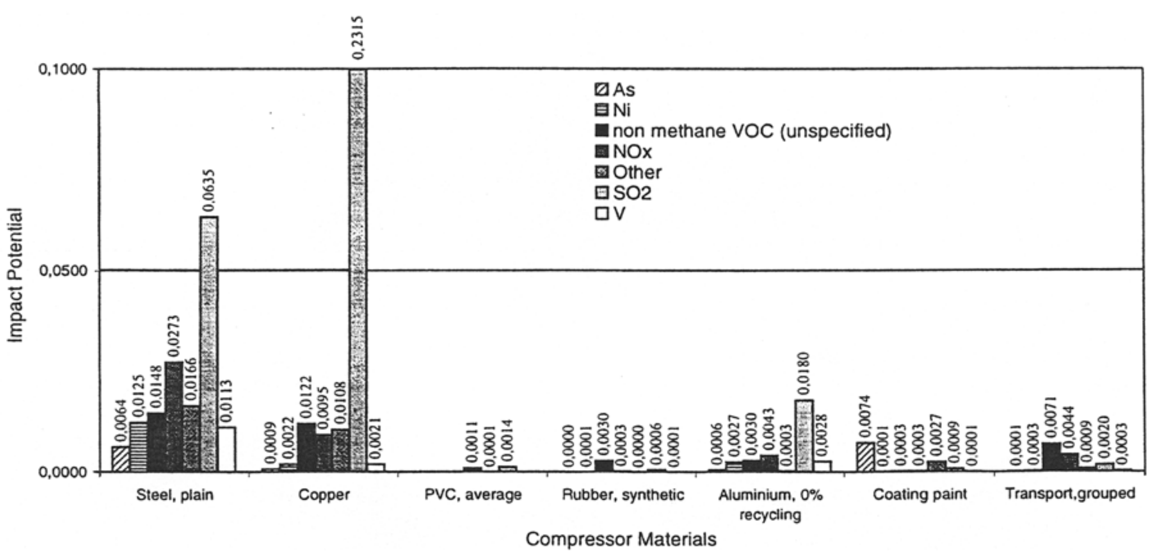

Fig. 10: The contribution of the individual compressor components to human toxicity

pressor are analysed. In actual fact, as given in **Table** 2, the compressor consists of a number of other materials.

To follow the investigation on the compressor more fully, the largest contributions identified in Fig. 6, that is, GWP, acidification and human toxicity, were individually assessed to study the influence that the individual compressor component materials have (**Fig.** 8, **Fig.** 9 and **Fig.** 10 respectively). It should be noted that the transport for all the individual materials was combined since individually, its value of contribution becomes insignificant. Once again the energy required for the manufacture of the compressor was ignored for these characteristics. It should be noted that the LCA software identified these elements but the magnitude of the values need to be looked at in more detail since in an environmental assessment the smallest values need not imply the least environmental impact.

3 Discussion

The production of HFC-134a approximately contributes to 57% more to the GWP due to CO_2 than the production of CFC-12 does. Hence, because this CFC-substitute reduces the direct GWP but not the indirect GWP, it is only from an ODP viewpoint that the environmental benefits have been realised for certain. If it was possible to reclaim all gases after use and ensure that systems do not leak over their entire lifetime then the global warming environmental benefits of replacing the CFCs would be reduced. Considering the four fuel scenarios, the mixed scenario as considered in this study is the most environmentally friendly. Findings show that if refrigerant gases are manufactured in low market economies, where the use of coal is likely, the environmental impact will be more dramatic for the CFC-substitutes. Manufacturers are likely to overlook this since subcontractors from low market economies are likely to be more competitive in price.

When considering acidification, it would be better if the gases are produced using natural gas; a significant difference of approximately 87% was found, from values given in **Fig. 2**, for oil and gas values respectively. As for GWP, the acidification resulting from the production of HFCs is larger by approximately 56% again due to the increased energy required during manufacture. The values for acidification resulting from the recovery of the gases under the different scenarios are identical and insignificant compared to those resulting from the production of the compounds.

The impact categories identified to be the most influential in **Fig. 3** were characterised by the energy consumption, assumed to be 18,000 MJ, throughout the use phase of the product. This is important since it primarily addresses issues that influence directly the energy consumption due to the choice of system lubricants. However, such disclosures have been previously made and to this effect the results obtained in this study compare well, particularly for the GWP (WENZEL et al., 1997). The present study preferred to treat the effect on abiotic depletion, highlighted in Fig. 3 and **Fig. 4**, with caution since this issue is highly controversial as precise quantities on remaining reserves is subjective and heavily dependant on economics, new technologies, discoveries of natural resources, etc. Nonetheless, results obtained for the GWP will be of significance when an assessment of the energy consumption in the use phase, using a variety of oil viscosities, will be obtained. This LCA study will help integrate experimental findings currently being undertaken to study this impact category more fully.

The refrigerating unit components identified in previous studies to be of larger environmental significance have been supported throughout this study. However, some other components as given in **Fig. 5** and **Fig. 6** have been found to play a significant role. The door lining, the thread shelves as well as the plastic boxes were of particular concern. The refrigerating compressor, again a focal point of this research work, has been identified as the second item of a refrigerating unit to be of significance in terms of impact potential. It is interesting to note how high the contributions to human toxicity, acidification, GWP and summer smog were as compared to its counterparts. Note that with some of these impact categories, human toxicity say, the inventory data is incomplete as compared to global warming say. Nonetheless, work still needs to be carried out until such inventories are completed. With the computational tool used in this study values of human toxicity obtained for different components are comparable since the same inventory is used throughout. Conclusions may be stated, with some caution, since impacts are more likely to increase as more is learnt on their inventories. Another observation made from these two figures is how large a contribution the energy for the production of the components has on the overall result. To follow closely the influence of the component materials this energy content has been completely ignored (→ *Fig. 6*). This influence should be treated with caution, in particular for the compressor's manufacturing process which must be energy intensive. It is also worth mentioning here that, due to its success, the hermetic compressor is nowadays being manufactured in developing regions such that the transportation of these components becomes significant. In this study, the compressor was taken to be transported from mainland Europe but compressors manufactured in the Far East are known to be used within European products.

The materials being used very heavily influence some of the impact potentials given in **Fig. 6**. Consider, for example, the cabinet insulation and the door insulation for which the production energy does not have a significant impact on the overall result. This GWP significance is maintained even though in this study it was assumed that no leakage of foam blower occurred throughout its lifetime and that it was fully reclaimed prior to its disposal. Both these assumptions need to be scrutinised since it is not yet mandatory to reclaim HFC refrigerants and hence the environmental impact would in effect be greater.

Whilst emphasising the assumption that all refrigerants and foam blowers were reclaimed and all materials were landfilled at their end of life, the steel cabinet proved to be the major contributor to the GWP. If we assume material reclaim then the significance of the components on the impact categories alters once again. However, considering the fact that recycling may not necessarily be the optimal sustainable choice due to the energy required and the quality of the recyclate, it is not misleading to assume that all the materials entering a refrigerator come from primary resources. As far as the compressor is concerned this seems to be the most likely course of action since it is thought that the energy required to access and reclaim any of its accessories is too high due to its hermetic configuration. It is thought that environmental benefits can only be attained if the component is immediately reused.

The base plate, hinge fittings, mounting rail, sealing frame and threaded portion become less significant without their energy of production content. Some energy definitely needs to be allocated to them but these items were not thought to be of particular concern here. Finally, as given in **Fig. 7**, the type and quantity of the materials making up the domestic refrigerating compressor are key to the overall outcome of the LCA result. The type of steel used in the compressor, in particular in the heavy outer shell of the unit, also accounts for approximately 50% of the indirect GWP due to CO_2. As seen in **Fig. 8**, **Fig. 9** and **Fig. 10** the individual materials which make up the compressor attribute different values to the impact categories investigated. Copper from the motor winding, for example, contributes mostly to acidification and human toxicity through SO_2 but also accounts for a significant percentage of CO_2, which influences the indirect GWP. Steel contributes to the CO_2 whilst its NO_x contributes to acidification and human toxicity too. Aluminium is also contributing significantly to hexafluoroethane and tetrafluoroethane influencing the GWP.

4 Conclusions and Outlook

Given the boundaries within which this study was carried out as well as the observations mentioned above the following conclusions are derived.

Product developers are faced with the task of having to comprehend scientific information ranging over many disciplines to be made aware of their design decision consequences. This study has highlighted how complex environmental issues in product development may become due to the differ-

ent engineering fields which influence them. It is hoped, however, that this on-going research as well as similar studies will assist designers understand the problem structure from a tribological viewpoint and present the various routes available to them to be able to make decisions with the least side effects. An awareness on the environmental finiteness will make such issues an integral part of design.

When addressing the GWP, the indirect contribution, that is, that part of the contribution resulting from the generation of the electricity used in the manufacture of refrigerants in particular, is key to the investigations. This observation is fundamental and influences the overall global warming emissions which are seen to reduce with the banning of CFCs. Acidification too plays a key role in this change in refrigerants with HFC compounds contributing 1.5 times when compared to CFCs. If the cooling capacity of the hermetic compressor is set to drop with HFCs than more refrigerant needs to be used causing a further increase in these impact categories.

Emphases on the hermetic compressor need to be intensified given its contribution to a number of impact categories. A thorough investigation on the individual components and their manufacturing needs to be performed using LCA methodology. The hermetic compressor is considered to be a durable product and therefore does not lend itself easily to reuse. However, the contribution to the environmental impact potentials identified to arise from the copper winding, for example, could motivate the possibility of its immediate reuse in the development of new motors. Due to the ban on CFC, reuse of components from CFC refrigerators is unrealistic (DTI, 1999). This needs to be re-addressed since by the time HFC products currently being produced near their end-of-life this compound is likely to be banned too delaying further component reuse.

The product use phase is likely to be influenced by the type of lubricant mixed with the refrigerant. To this effect this study has highlighted the importance of functional tests currently being carried out to monitor the energy requirement using a variety of lubricant viscosity grades and how these affect product performance and durability from an environmental viewpoint. Refrigerator efficiency becomes a key role when considering that emissions of CO_2 are being regulated (Kyoto Protocol) and yet they are likely to triple between now and 2050 (Campbell et al., 1998).

Acknowledgements

The authors would like to acknowledge the Engineering and Physical Science Research Council (EPSRC) of the UK for funding this three year research project. The authors also wish to thank Mr. Michael Sturges at Pira International, UK as well as the anonymous reviewers of this report for their constructive comments.

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Received: October 7th, 1999
Accepted: February 4th, 2000
Online-First: April 13th, 2000